

NON-CONTACT EDDY CURRENT HOLE ECCENTRICITY AND DIAMETER MEASUREMENT

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ABSTRACT

Precision holes are among the most critical features of a mechanical component. Deviations from permissible tolerances can impede operation and result in unexpected failure. We have developed an automated non-contact eddy current hole diameter and eccentricity measuring system. The operating principle is based on the eddy current lift-off effect, which is the coil impedance as a function of the distance between the coil and the test object. An absolute eddy current probe rotates in the hole. The impedance of each angular position is acquired and input to the computer for integration and analysis. The eccentricity of the hole is the profile of the impedance as a function of angular position as compared to a straight line, an ideal hole. The diameter of the hole is the sum of the diameter of the probe and twice the distance-calibrated impedance. An eddy current image is generated by integrating angular scans for a plurality of depths between the top and bottom to display the eccentricity profile. This system can also detect and image defects in the hole. The method for non-contact eddy current hole diameter and eccentricity measurement has been granted a patent by the U. S. Patent and Trademark Office.

INTRODUCTION

Holes in general are one of the most common features of a mechanical component. In precision applications, eccentricity and diameter of the holes directly relate to the performance and even service life of the component. Deviations from permissible tolerances can impede operation and result in pre-mature failure of the system. It is thus important to inspect and validate the dimensional accuracy, such as eccentricity and diameter of the holes. Many state-of-the-art hole inspection devices are available, such as hole gauges, dowel pins, and capacitance hole probes as well as eddy current hole measuring instruments. However, most of these devices are often operator dependent and have limited capabilities, resulting in compromised accuracy, reliability, and repeatability.

We have developed an automated non-contact eddy current hole diameter and eccentricity measuring system. The operating principle is based on the eddy current lift-off effect, which is the coil impedance as a function of the distance between the sensing element and the test object. This system consists of three functional components: a data acquisition subsystem, a mechanical subsystem, and an eddy current measuring subsystem. A PC is used as the system controller for mechanical control, data acquisition, signal processing, and analysis. The mechanical subsystem includes a computer controllable multi-axis stage and a specimen-mounting fixture. The eddy current instrument subsystem consists of an impedance analyzer and a rotational eddy current probe scanner.

An absolute eddy current probe rotates in the hole. The impedance of each angular position is acquired and input to the computer for integration and analysis. The eccentricity of the hole is the profile of the impedance as a function of angular position as compared to a straight line; this profile constitutes an ideal hole. The diameter of the hole is the sum of the diameter of the probe

and twice the distance-calibrated impedance. An eddy current image can be generated by integrating angular scans for a plurality of depths between the top and bottom to display the eccentricity profile of the hole. This system can also be used for detecting and imaging defects in the hole as a typical eddy current hole inspection system.

In this paper, we review the basic principle of eddy current lift-off effect, describe the non-contact eddy current hole measuring system, and present test results of laboratory experiments. Potential areas of applications include process qualification, process monitoring, quality assurance, and inspection of new and refurbished hardware. The method for non-contact eddy current hole diameter and eccentricity measurement has been granted a patent to NASA by the U. S. Patent and Trademark Office. This system is readily available for technology transfer and licensing.

BACKGROUND AND ANALYSIS

Due to its sensitivity to discontinuity, nondestructive eddy current method is widely used for defect detection and characterization by the evaluation engineering industry [1, 2]. It is also known that the eddy current coil impedance is also very sensitive to the distance between the sensing coil and the test object; this is the lift-off effect. Figure 1 shows the eddy current impedance as a nonlinear but monotonic function of lift-off distance. This eddy current lift-off effect is considered detrimental to nondestructive testing applications. However, when it is properly calibrated, it can be used for many distance-sensing applications such as proximity sensors [3]. In our specific applications, we utilize this eddy current lift-off effect for rotational hole eccentricity and diameter measurements [4].

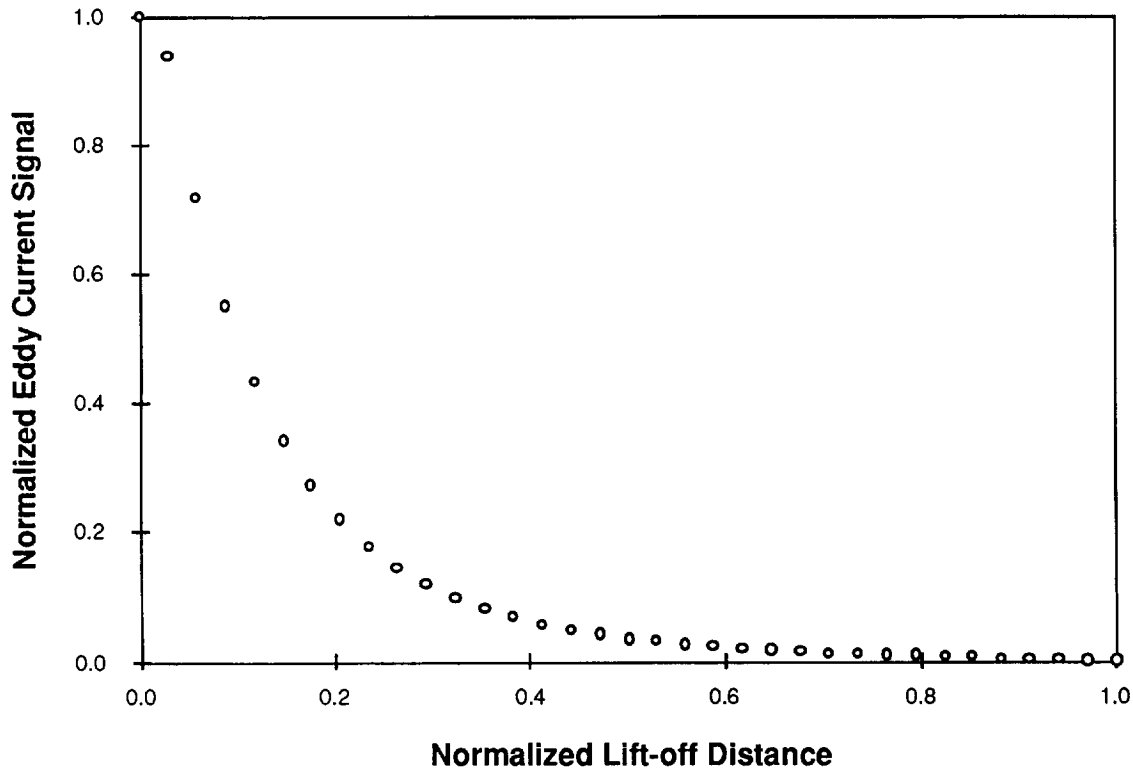


Figure 1. Eddy current signal amplitude as a function of lift-off distance.

Probe Centering

For non-contact hole measuring applications, the presumption is that the eddy current probe is at the geometric center of the hole. However, this may not always be the case when the probe is first placed inside the hole. It is thus necessary to develop a process to center the probe before performing eccentricity and diameter measurements. We consider the rotational eddy current probe is (ℓ, θ_0) off-center as shown in Figure 2. With some trigonometric and mathematical manipulations, we can obtain an analytic expression of lift-off distance $\ell = \ell(\ell_0, r_h, r_p, \theta_0, \theta)$, for the probe at a given angle, θ as [5]

$$(1) \quad \ell = -r_p - \ell_0 \cos(\theta - \theta_0) + [r_h^2 - \ell_0^2 \sin^2(\theta - \theta_0)]^{1/2}$$

where r_p is the radius of the probe, r_h is the radius of the hole, and ℓ is the lift-off, i.e., distance of the probe coil tip to the surface of the hole. When the probe is centered in the hole, $Z(\ell, \theta)$ is minimized.

Since the angular dependent lift-off function (Equation 1) is continuous, the impedance $Z(\theta)$ is a low-frequency response. The period of this low-frequency curve directly corresponds to the rotational speed of the probe. To center the probe is essentially to minimize the off-centered distance ℓ_0 (or to compel $\ell = r_h - r_p$ resulting from Equation 1 for $\ell = 0$). Since the X-axis and Y-axis are orthogonal for the Cartesian coordinates, it can be shown that to minimize ℓ_0 is equivalent to minimizing ℓ_x and ℓ_y where $\ell_x = \ell_0 \cos\theta_0$ and $\ell_y = \ell_0 \sin\theta_0$. In practice, this made it possible to manipulate the mechanical X and Y axes independently for the probe centering process, i.e., minimizing the $Z(\ell, \theta)$ with mechanical manipulation of the X and Y axes.

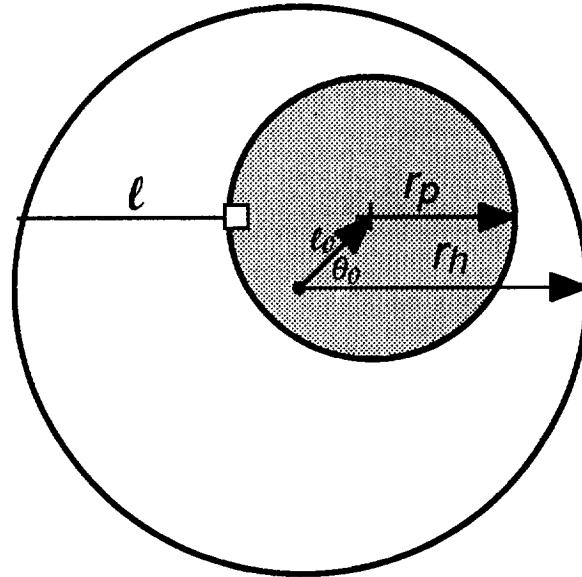


Figure 2. A sketch of the rotational eddy current probe in a hole specimen.

Hole Eccentricity and Diameter Measurement

After the absolute eddy current probe is centered in the hole, the eddy current impedance signal is digitized and acquired by the data acquisition system for analysis. A plot of the impedance as a function of probe angular position is generated. A software algorithm can be written to include probe diameter and display the calculated diameter of the hole as

$$(2) \quad d_h = 2 r_p + 2 \ell$$

where d_h is the diameter of the hole and ℓ is the average lift-off distance around the hole. Eccentricity of the hole can be determined by plotting the difference of the measured diameter and the calculated diameter d_h for each angular position. An example of the measuring result is shown in Figure 3. The data can be presented as a function of angular position in either Cartesian or polar coordinates. An eddy current image can also be generated by integrating angular scans for a plurality of depths between the top and bottom to display the eccentricity profile of the hole (Figure 4).

HARDWARE SETUP AND TEST PROCEDURES

The non-contact eddy current hole eccentricity and diameter measuring system consists of three functional components: a data acquisition subsystem, a mechanical subsystem, and an eddy current measuring subsystem. Figure 5 shows the block diagram of the system. A PC is used as the system controller for mechanical control, data acquisition, signal processing, and analysis. The mechanical subsystem includes a computer controllable multi-axis stage and a specimen-mounting fixture. The eddy current instrument subsystem consists of an impedance analyzer and a rotational eddy current probe scanner.

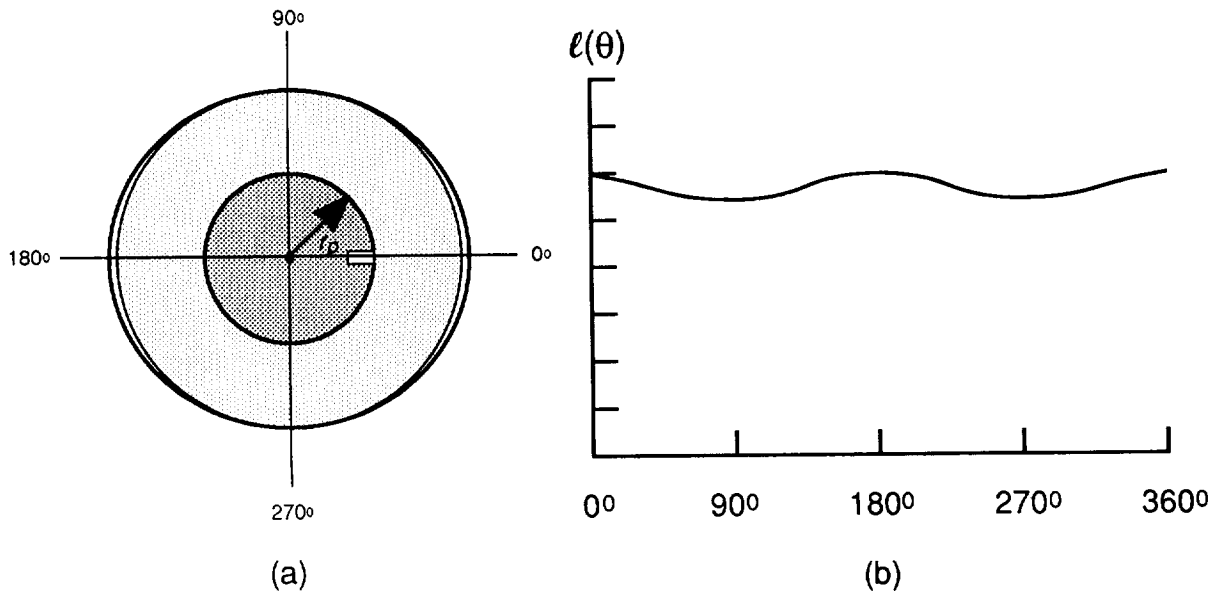


Figure 3. Eddy current hole eccentricity and diameter measurement: (a) rotational eddy current probe in a hole specimen and (b) signal response with respect to probe angular position.

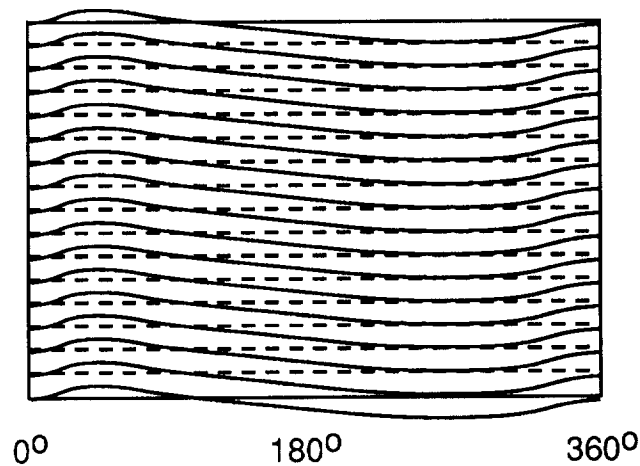


Figure 4. Eccentricity and diameter profile of a hole specimen. Dashed line representing an ideal hole.

The eddy current signal of the hole is obtained from the rotating probe, which is driven by an eddy current instrument. A Personal Computer (PC) is used as the system controller to digitize the eddy current signals, perform signal processing, and command the mechanical manipulator to move the probe to the desired coordinate. A mathematical algorithm is used to determine the dominant parameter and to center the probe. It basically follows the analysis and argument of the previous section. The accuracy of the centering process is limited by the signal-to-noise ratio of the eddy current instrument.

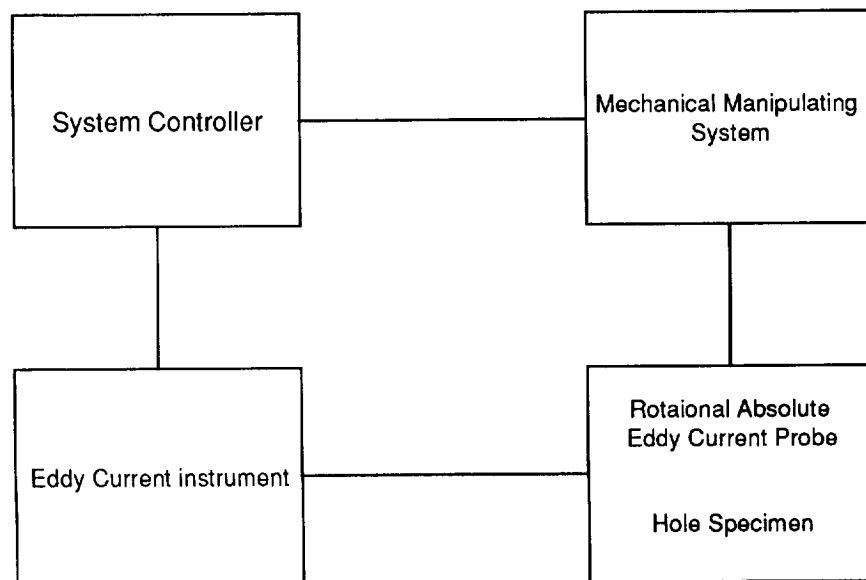


Figure 5. Block diagram of the rotational eddy current hole eccentricity and diameter measurement.

DISCUSSION AND CONCLUSION

The eddy current signal decreases drastically with the lift-off distance. The sensitivity of a probe also proportionally decreases with the hole size. Typically, the most effective operating range for a probe is when the diameter of the hole is within 5 mm of the diameter of the probe. For this reason, the selection of an appropriate eddy current probe is essential to achieve a desired sensitivity and accuracy. To accommodate a wide range of holes, an inventory of various diameter probes becomes necessary. To simplify the operation, a special diameter-adjustable probe or a multi-coil probe of various diameters can be designed. Examples of advanced probe designs are shown in Figure 6. A smaller diameter probe is used to center the probe, and an appropriate diameter is used to perform the eccentricity and diameter measurements. Since the fundamental configuration of the probe is similar to that of an absolute eddy current probe for defect inspection, the system can also be used to detect and image defects.

Advancements in digital electronics technology and personal computers have enabled the development of many computer-controllable instruments. Instruments can be integrated into the PC platform by using plug-in boards, through various interface buses for stand-alone digital instruments, or through an A/D card for analog instruments. These advances have facilitated the integration of various functional equipment into an automated engineering workstation. The CAD/CAM design of a test object can be used to position the probe in close proximity of the hole. A smaller diameter probe is inserted in the hole and centers the probe with respect to the hole. The algorithm based on Equation 1 is used for the centering procedure. An appropriate diameter probe is then used to determine the eccentricity and diameter of the hole. A polar plot, 2-D line plot, and an image of the hole are generated to display the results.

In summary, we have presented an innovative rotational eddy current eccentricity and diameter measuring technique. We have reviewed the operating principle and presented a unique technique for probe centering and inspection. The results obtained from the experiments also clearly demonstrated the validity of the system. The method for non-contact eddy current hole diameter and eccentricity measurement has been granted a patent to NASA by the U. S. Patent and Trademark Office [4]. The system can be used for inspection of critical aircraft engine components and other precision machinery. This system is readily available for technology transfer and licensing.

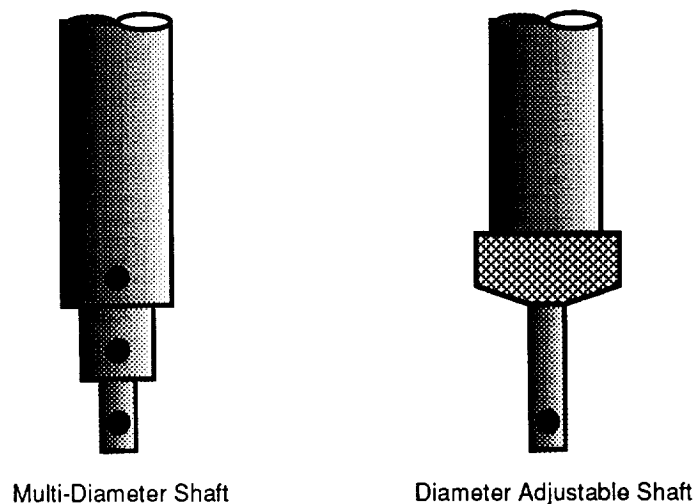


Figure 6. Advance probe designs with multi-diameter and diameter adjustable shafts.

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